



Survivability Analysis for the Evaluation of Personnel in Body Armor

by Natalie Eberius and Patrick Gillich

ARL-RP-304

October 2010

**A reprint from the *PASS Proceedings*,
Quebec City, CA, 13 September 2010.**

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Natalie Eberius and Patrick Gillich
Survivability/Lethality Analysis Directorate, ARL

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Abstract. The U.S. Army performs combat system survivability/lethality/vulnerability (SLV) analyses using a software package called MUVES-S2. MUVES-S2 is an Army developed and maintained SLV computer model capable of analyzing the effects of one or more munitions against aircraft or ground-mobile targets and personnel. A new approach to personnel survivability and casualty assessment has been developed by integrating the Operational Requirement-based Casualty Assessment (ORCA) modeling system into MUVES-S2. ORCA is the tri-service developed personnel model and provides improvement for all phases of the casualty assessment process including more precise anatomical representation, mapping of insult(s) to injury evaluation, mapping injury to medical casualty characterization, mapping injury to physical and cognitive impairment, mapping job and task requirements to basic human capabilities, evaluating basic human capability requirements to post-injury capabilities, and calculating operational casualty metrics. This paper presents an overview of the MUVES-S2/ORCA methodology, highlighting improved capabilities and new techniques for performing SLV analyses of personnel wearing various body armor configurations. We will show how body armor survivability studies incorporate the use of injury characterization to quantify the vulnerability of a protective system against an understood threat. The ability to model small changes in personal protective equipment and their effect on personnel survivability will also be demonstrated.

1. ISSUE

The Army Research Laboratory Survivability/Lethality Analysis Directorate (ARL/SLAD) has conducted several analyses of military body armor survivability during the Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) conflicts. These analyses were conducted after a system was either fielded or after its development was complete. The purpose of these analyses was to either compare enhancements to current system capability or to further understand unique scenarios presented in the current conflicts. The lesson learned in these survivability studies was that the revelations of system vulnerabilities could have been utilized to improve the initial design of the body armor system prior to fielding.

2. BODY ARMOR ANALYSIS PROCESS / WHAT WE DO

Maximizing protection provided by military body armor is an exercise in optimizing coverage of critical body regions while permitting the user necessary battlefield efficiency. The ballistic protection is clearly a key factor in the grading of body armor; however, it is one of many factors that determine its overall effectiveness. The other factors are assessed through user tests in operational scenarios or scenarios that exercise specific user functionalities. Some of the various requirements considered are: weapon accuracy, battlefield signature, weight of system, thermal regulation, maneuverability, range of motion, situational awareness, comfort, as well as the interaction of the body armor system with other personnel equipment. Other time-sensitive factors considered include: access to first aid, emergency don/doff, evacuation, vehicle ingress/egress, reassembly, and individual movement techniques. These factors are measured independent of the ballistic grading and are accumulated to complete a comprehensive system analysis.

ARL/SLAD conducts body armor system analysis using modeling and simulation (M&S) to analyze threats versus personnel wearing various body armor systems. The analysis outcomes can show differences in the protection provided by different systems and reveal system strengths and vulnerabilities. This paper will focus on the protection offered by body armor from ballistic penetration threats, both direct and indirect. A survivability assessment process is discussed that describes how to conduct personnel and body armor analyses. This process is enumerated in five steps and depicted in Figure 1.

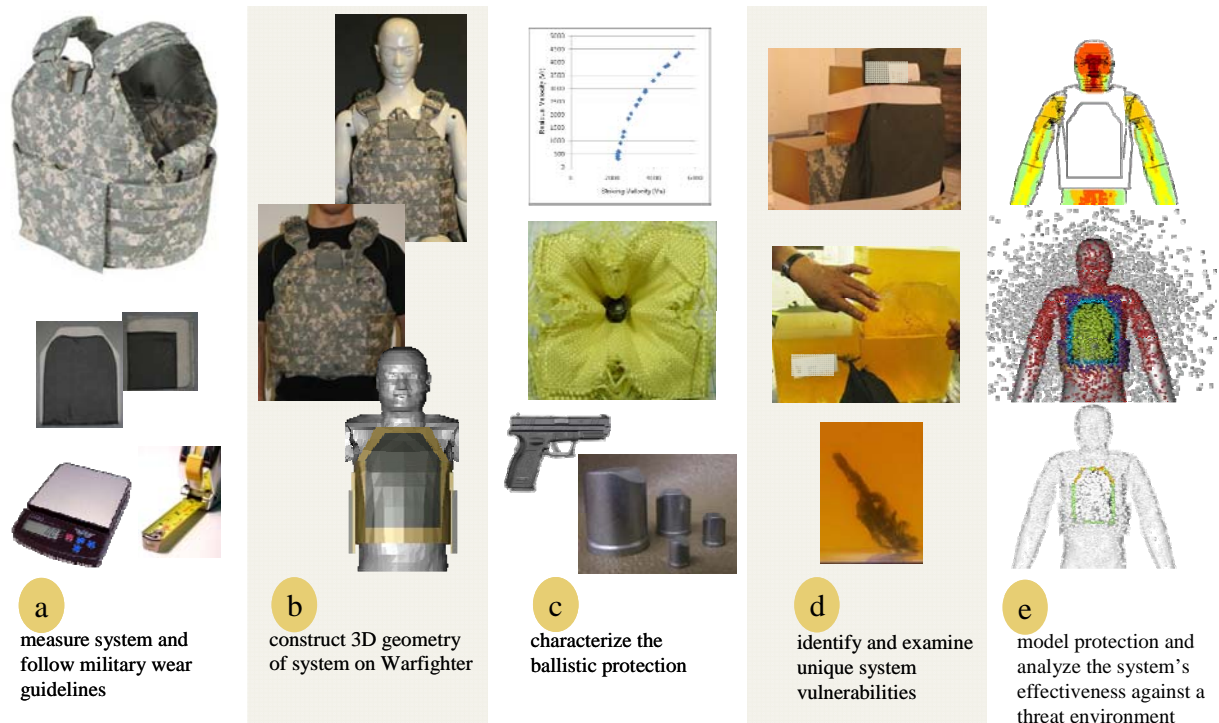


Figure 1. Body Armor Analysis Process

3. PROCESS STEP ONE: MEASURE SYSTEM DIMENSION AND FIT

In order to properly construct a model of a body armor system for survivability analysis, physical dimensions of the system as well as its anatomical location on the Warfighter is needed. The physical dimensions of the system are acquired using basic measurement techniques with enough resolution to support anatomic fit. Understanding system fit on the Warfighter is critical because it determines the area of the body protected. Military wear guidelines for body armor dictate proper configuration and wear of the system. Fit analysis is recommended using anthropomorphic mannequins to initially match up anatomic surface landmarks with the wear of the system. Measurement of system fit on volunteer Warfighters are performed in parallel with the mannequin measurements. Testing wear on human volunteers provides the needed confidence of how a system will conform to the human body.

Body armor survivability analyses are typically performed with a discrete fit for each system. This fit falls within the range dictated by military wear guidelines. The determination of a discrete fit allows for comparative analyses between body armor systems. The discrete fit is selected for each system in a manner so as not to bias the comparative analysis. However, variability in proper fit exposes the Warfighter to a range of vulnerability that can be measured and assessed. This described range of vulnerability can be used to further understand a given system. An example that illustrates a range of proper fits is the allowed forward and backward tilt of the combat helmet. The helmet can tilt $\pm 3^\circ$ and thus vary the exposure of critical regions of the head to ballistic impacts.

Lesson learned 1: Much analysis time should be spent on understanding the dimensions of the body armor system when coupled with the Warfighter.

4. PROCESS STEP TWO: CONSTRUCT THREE DIMENSIONAL GEOMETRY

A geometric model of the body armor on a reference digital anthropomorphic model must be constructed in order to perform a ballistic analysis. The digital anatomic representation must contain surface topology with its underlying anatomic structure described at the tissue level (muscles, vessels, organs, etc). This will enable the identification of surface landmarks and their mapping to the underlying anatomic structure. The two classes of body armor that are modeled and undergo ballistic analysis are soft and hard body armors. The soft body armors are flexible and can conform to the individual wearing it; these are typically the vest and its accoutrements such as deltoid protection, neck protection and groin protection. The hard body armor is the helmet and ballistic plates. Survivability results from ballistic analysis are extremely sensitive to the proper construction of the body armor as well as its placement on the anatomy. The creation of this armor begins with fitting the correct body armor size onto the digital anatomy. Due to the flexible nature of soft armor, the geometry often needs to be modeled with a different process than hard armor. The soft armor vest contains ballistic protection elements which are typically hidden under a makeup of coverings, fasteners, pouches, and webbing. Often the ballistic protection is sewn into the system or uniquely embedded to allow for removal. For the purposes of ballistic modeling of soft armor, the actual ballistic armor is the only part of the vest that will undergo ballistic analysis. The complexity of the armor might require removal for proper dimensionality and shape measurements. From this description, coupled with any available design diagrams, the armor can then be modeled in CAD software. Hard armor modeling is more straightforward because it can leverage laser scanning capabilities to describe its dimensionality; however, this requires prepping of material to guarantee the best possible scan. For these scans, post-processing of the geometry is required to clean up edges and verify dimensions.

The elements of the target that must be constructed are the digital anatomy wearing the soft and hard armor while assuring that the anatomy and the body armor do not overlap. The analysis simulates threats hitting the target and proper geometric fidelity is necessary for the model to evaluate the components that are being assessed. The analysis is performed in the vulnerability model MUVES-S2 which embeds the Operational Requirement-based Casualty Assessment (ORCA) model as its personnel module.

Lesson learned 2: The focus of soft armor modeling is identifying the subset of material that provides ballistic protection for accurate measurement.

5. STEP THREE: CHARACTERIZE BALLISTIC PROTECTION

Survivability analysis for body armor systems requires the examination of ballistic protection. The protection level of body armor is determined by ballistic limit tests on representative samples to determine ballistic performance. Ballistic protection levels support two unique threat classes, indirect fire (fragments) and direct fire (small-caliber munitions). The ballistic grading criteria for both threat classes is the ballistic limit which is determined through V_{50} ballistic limit tests and, in some cases, V_0 ballistic limit tests where the armor is shot by threats that it is designed to defeat. The V_{50} ballistic limit is the velocity at which penetration of the armor occurs 50% of the time or the velocity estimation at which complete penetration and incomplete penetration are equally likely to occur. The V_0 ballistic limit is the highest striking velocity at which the probability of a complete penetration is zero or the maximum velocity at which a particular projectile is expected to consistently fail to penetrate armor at a specified obliquity. The V_{50} value is typically used in body armor testing for a variety of reasons, the most common being the number of shots and therefore expense required to calculate a V_0 is significantly higher than the number needed for a V_{50} . Statistically, V_0 is the end of the probability distribution curve, and its determination is confounded by the large variability involved in material and test. These reasons account for the use of the V_{50} statistical approach.

Indirect fired threats (i.e., bursting munitions) are simulated in test through direct firing of fragment simulating projectiles (FSPs) at controlled velocities. The FSP threat matrix usually includes 2, 4, 16 and 64 grain right circular cylinder (RCC) steel projectiles fired at a range of striking velocities. More involved fragment testing characterizes the residual velocity (V_r) for a given striking velocity (V_s) for multiple striking obliquities (typically 0° and 45°). This testing measures the ability of the body armor

material to completely stop or reduce the velocity of fragments over a range of impact conditions. Empirically-based mathematical models can be derived from V_s versus V_r curves and used to describe relationships between properties of the projectile and material target. It is advantageous to have the V_s/V_r relationships because it gives a higher resolution description of the protection of the material and supports the larger range of ballistic engagements that can be simulated in a vulnerability model. Additionally, the V_0 ballistic limit can be approximated from the V_s - V_r curve.

Direct fire threat testing does not benefit from the same type of rigor seen in V_s/V_r testing done for indirect fire threats. Materials and systems are designed according to direct fire specifications usually at muzzle velocities. These protection levels are validated when the body armor system is undergoing evaluation for fielding by ballistic acceptance tests on representative samples to determine whether or not the lot of armor is ballistically acceptable for use. Most of the time, body armor is not ballistically tested outside its specified protection level which is often defined in its purchase description.

Lesson learned 3: Vulnerability modeling of body armor systems involves a range of penetration threats that require additional testing outside of what the system is required to support.

6. STEP FOUR: IDENTIFY AND EXAMINE UNIQUE VULNERABILITIES

New designs and materials can introduce unique vulnerabilities, capabilities and limitations. As better systems are designed, developed and fielded, the analyst needs to be vigilant with their assessment to make certain that a comprehensive evaluation is conducted. These unique vulnerabilities are often revealed and understood through engineering review and experimental testing. One such vulnerability that is not exclusive to the domain of body armor is the performance degradation seen on the edges of the armor. Depending on the gradient change in protection across the surface of the material, it can become important to better examine these areas of a body armor system. An example of a unique vulnerability is ballistic failure where hard armor is expected to perform. This vulnerability is geographically located on the outer edge of a plate located within required performance parameters. This is illustrated in Figure 2 where the red region is not required to meet specific performance requirements and the black region in the center of the plate must meet specific performance requirements. Armor edge failure occurs when shots on the edge of the black region defeat the armor. This failure can be either be a penetration of the armor or a break-up of the projectile where fragments blow out of the side of the armor. In the case of break-up, we can model the potential injury to the Warfighter from these fragments. The approach to characterize this potential threat included an adaptation of experimental techniques where the break-up behavior could be replicated and fragmentation characterized. This experimental setup collected the fragments in ballistic gelatin. The necessary ballistic characteristics were determined by a combination of the orthogonal high-speed video and collection of the fragments from ballistic gelatin. The characteristics of trajectory, material, velocity, mass and shape factor were used as input to the MUVES-S2 and ORCA modeling system to predict the frequency, type and severity level of injury expected to occur from the collected test data. The experimentation also identified the frequency of edge failure occurrence. A depiction of the experimental setup to collect this information and the process to assess injury is shown in Figure 3.



Figure 2. Hard Armor Edge Vulnerability

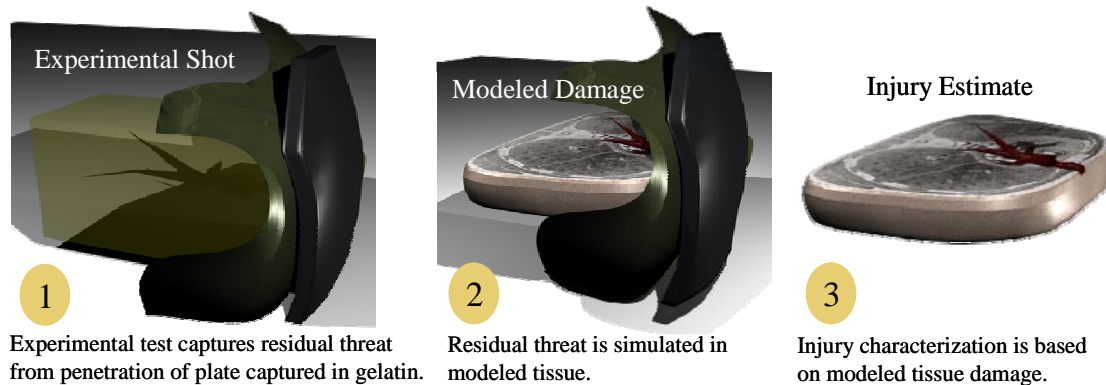


Figure 3. Ballistic Gelatin Testing to Support Injury Analysis

Lesson learned 4: Edge effects of small-arms ballistic inserts are important to examine because they may represent a large area of the armor system.

7. STEP FIVE: MODEL PROTECTION AND MEASURE EFFECTIVENESS

Identifying injury type, size, severity and frequency is critical in the evaluation of body armor systems. These metrics identify Warfighter survivability and reveal differences between armor systems. The Abbreviated Injury Scale (AIS) is the most widely used anatomically-based injury classification system for describing personnel trauma which uses a standardized terminology, ranks injury by severity, and facilitates comparisons for injury study. The AIS describes the impact of an injury in terms of the extent of tissue damage and generally defines severity in terms of "threat to life". It is regarded as the best injury coding scheme for blunt and penetrating trauma. Every injury describable in the AIS system is assigned a unique six-digit numeric code. Every six-digit numeric code in AIS is associated with a seventh post-dot digit classifying injury severity (see Figure 4). The severity score is a six-point ordinal scale with levels that range from 1 (relatively minor) to 6 (maximal or virtually unsurvivable). The AIS-based measure of effectiveness often preferred for body armor analysis is the Maximum Abbreviated Injury Scale (MAIS). This score summarizes the severity of a penetrating insult by taking the maximum severity score for all anatomical injuries sustained. A MAIS of 0 indicates no AIS scores were generated for the associated injury.

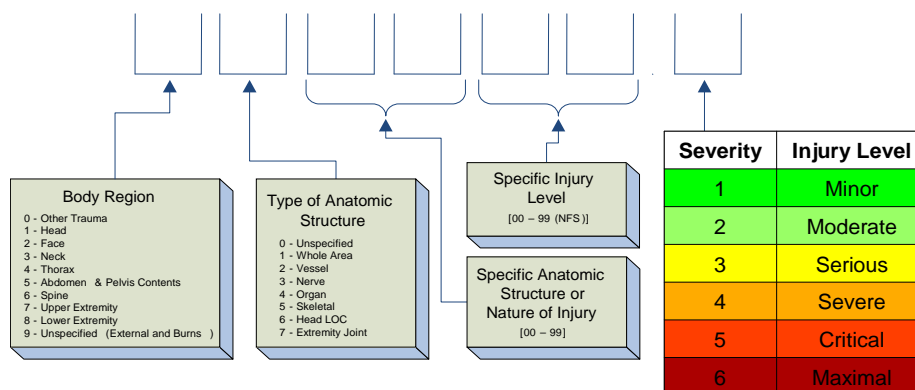


Figure 4. AIS 2005 (update 2008) Numeric Notation

Military combat injuries stored in trauma registries are coded in AIS. The U.S. Army personnel modeling software, ORCA, computes military combat injuries using the AIS 2005 (update 2008). ORCA incorporates descriptors that support the coding of penetrating injuries as well as other damage mechanisms. The standard lexicon of AIS allows for field data to be compared readily to predictions made by M&S. ORCA M&S allows us to explore the ramification of system design by investigating material effectiveness observed in actual operational context.

The MUVES-S2 software system provides the SLV analyst a tool that can provide realistic estimates of platform and personnel survivability and vulnerability against weapon effects. For modeling personnel with ORCA, MUVES-S2 combines the elements of target geometry, threat characterization, and associated damage mechanisms to determine weapon effects on personnel equipped with and without body armor. This model provides realistic predictions by tracing a threat's path and performing damage and residual threat calculations.

Body armor analyses have been successfully performed by ARL/SLAD through the use of MUVES-S2 and ORCA to assess protection and quantify system effectiveness. These analyses have supported fielding decisions and have provided relevant vulnerability information to the Warfighter. The important metric for quantifying system effectiveness is the ability of the system to protect against *significant injuries* as defined by AIS scores of serious (AIS 3) or greater. The serious level is selected as appropriate for the majority of analyses because it represents the threshold where there is a significant increase of threat to life and an immediate need for medical attention.

The two basic types of body armor analyses are: a) area of coverage (AoC) versus area of protection (AoP); and b) operational scenario modeling for direct and indirect fire threats. AoC is the amount of body surface area protected by the body armor system when worn properly. AoP is the area of coverage that protects against significant injury. Body armor systems are optimized in terms of weight and protection when these two areas numerically approach each other. In other words, a completely optimized system is one in which all the area covered by body armor is protecting the user from significant injuries.

7.1 Area of Coverage and Area of Protection Analyses

AoC analyses are accomplished by comparing the presented area of the target with the presented area covered by the system for which the body armor system provides protection. AoC analyses are performed using direct fire threats where the body is interrogated with shotlines using a uniformly spaced grid from multiple azimuths. An example of this kind of analysis is shown in Figure 5. A baseline protection level is applied for comparison. When a single system is being evaluated, the unprotected state without any system is used as the baseline. When an existing system that has been fielded is replaced or enhanced, the existing system's protection serves as the baseline. An example analysis is the comparison of a standard military vest and a plate carrier. The intent of a plate carrier is to provide a lighter weight alternative to the standard military vest. The risk of using a plate carrier as opposed to using the standard vest is reduced coverage. AoP analyses can be performed to quantify this risk in terms of threats to which the user could potentially be exposed and the associated severity of injury. A depiction of this type of analysis is shown in Figure 6, where we compare the AoC differences between a plate carrier and a standard vest as well as the severity of injury for areas protected by the standard vest and not by the plate carrier. These analyses are most effectively conducted when the grid interrogation uses fine grid spacing and intervals around the body. This interrogation technique is used to reveal the change in vulnerability as a function of angle of attack. The metric calculated from this type of analysis is the average area of coverage for a given azimuth. Once an AoC and AoP analysis has been performed, the total weight of the system is used to calculate its overall protection as a function of areal density. Armor optimization can be achieved by examining the ratio of the total weight of the system versus the area of protection. This is the amount of weight the user must carry to support the given protection level.

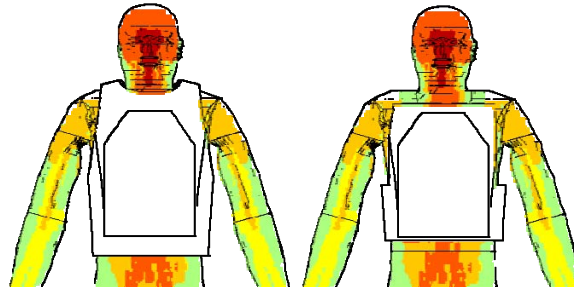


Figure 5. Example of Area of Coverage Analysis of Generic Vest (left) and Plate Carrier (right)

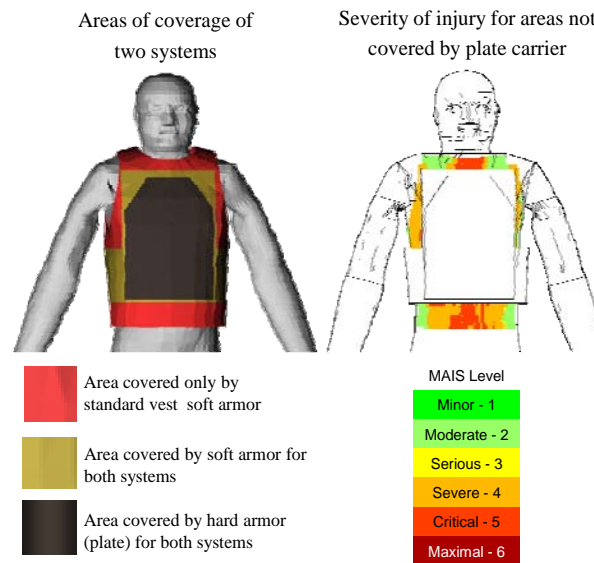


Figure 6. Area of Coverage and Area of Protection Analysis for Generic Vest and Plate Carrier

7.2 Operational Scenario Modeling for Direct and Indirect Fire Threats

AoC and AoP analyses typically serve as precursors to analyses that incorporate the user's threat environment. Operational scenario modeling includes identification of relevant threats and the ballistic capability of these threats against the body armor being assessed. The threat environment could include either a direct fire engagement, such as a rifle bullet, or an indirect fire engagement, such as a hand grenade. These analyses require a multiple step approach. The direct fire analysis steps include simulating weapon system dispersion to impacts on the body, deriving the probability of hitting the target, and modeling the injurious effects of each hit. The dispersion calculations take into account range and whether or not the target and shooter are static or moving. The probability of hitting the target is calculated from an error budget that includes the user, the system and the environment. The rifle round is simulated in flight from the shooter to the target to predict impact locations and their resultant effects. An example direct fire analyses is the edge effect study described in Section 6. For this particular analysis, the problem was to quantify the risk to the user of the projectile break-up phenomenon. The analysis involved three steps illustrated in Figure 7, which are the: a) simulate of rifle dispersion to derive probability of hit to the edge; b) compute probability of injury given a hit to the edge, assuming 100% probability of blow-out; and c) compute probability of injury given a hit to the edge, given the probability of break-up obtained from testing. This approach allows the determination of whether or not this vulnerability is significant.

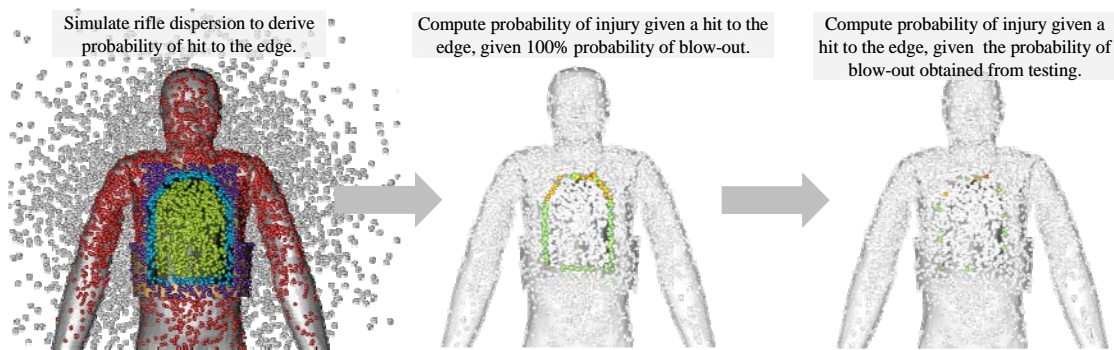


Figure 7. Process Steps for Direct Fire Analysis

Indirect fire analysis in support of body armor system evaluation involves characterizing the bursting munitions and their potential to cause injury to personnel. The lethality footprint of a bursting munition is obtained through the use of target arrays. In a typical analysis, a planar grid of cells is constructed and each target in the array is evaluated given a detonation. Figure 8 illustrates an example of this target array and an example of the elements in the grid plot. The characterization of the munition is described where the parameters of mass, velocity, shape factor, and trajectory angle are subjected to statistical variability. Another parameter that can be varied is the position of the target within the cell. This process allows the model to produce a distribution of burst results and generate a lethality footprint of the munition against the dismounted Warfighter showing the vulnerability to the munition. These footprints depict the effects of the munition in terms of the distance and orientation of the Warfighter relative to the detonation location.

The output from these types of analyses is displayed in contour plots where the metric can vary depending on the focus of the particular analysis. Some of the more common types of metrics are MAIS, probability of a specific MAIS level, number of hits to a particular personnel target and number of hits to particular body regions. An example plot is shown in Figure 8. This plot depicts model results of a bursting munition detonation from the grid space center and resultant effects on the target array of dismounted Warfighters. Each dismounted Warfighter in the array is independently evaluated for every cell.

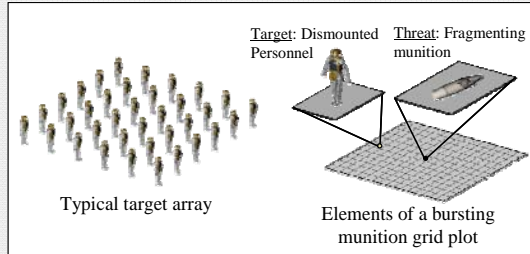
In addition to generating plots which represent the bursting munition's lethality in terms of effect on personnel injury, more specific information about the dismounted Warfighter is produced. An example is illustrated in Figure 9. The MAIS of the dismounted Warfighter is 5 (critical injury) and the cell that represents this location is color coded accordingly. The trajectories of all the fragments that caused injury can be modeled to aid in understanding the behavior of the threat. Injuries can then be mapped to the surface of the anthropomorphic geometric model where the threat trajectories intersect the body. The impact locations and areas of influence can be visualized in three dimensions and color coded according to the MAIS level received.

These analysis capabilities can demonstrate the utility of body armor systems designed to protect against the effects of bursting munitions. The comparison of armor systems can be easily measured and quantified to support performance measures and tradeoff analyses. These analyses can assist in understanding areas where protection provided by body armors influence survivability.

Lesson learned 5: Modeling the operational scenario in which the body armor is exposed is most relevant; this applies a weighting function to the protection offered by the system and supports risk analysis for fielding decisions.

Plot depicts model results of a fragmenting munition detonation from the grid space center and resultant effects on an array of dismounted Warfighters.

- Each dismounted Warfighter in the array is independently evaluated for every cell.



- Analysis output is the frequency of Serious (MAIS 3) or greater injury given a detonation.

- Detonation is evaluated stochastically where results are based on Monte Carlo methods.

Probability of a significant injury contour plot for a fragmenting munition against a dismounted Warfighter array

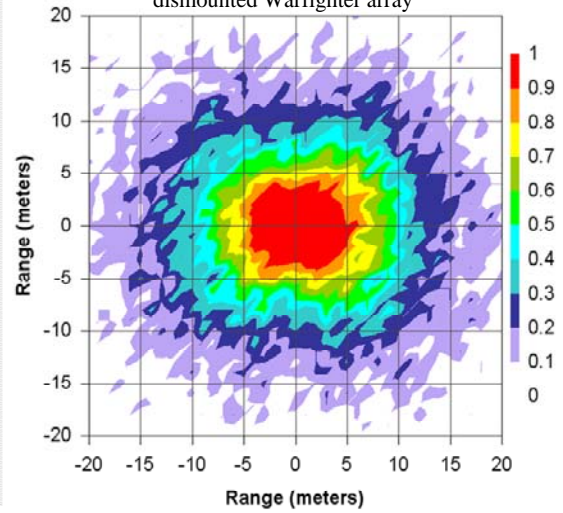


Figure 8. Indirect Fire Analysis for Body Armor Systems

AIS Injury Occurrence:

- 1 Critical injury (AIS 5)
- 3 Severe injuries (AIS 4)
- 2 Serious injuries (AIS 3)
- 1 Moderate injury (AIS 2)
- 7 Total injuries

Injury Example 1:

- Skull penetration greater than 2 cm
- Critical injury (MAIS 5)

Injury Example 2:

- Major artery rupture (transection)
- Serious injury (MAIS 3)

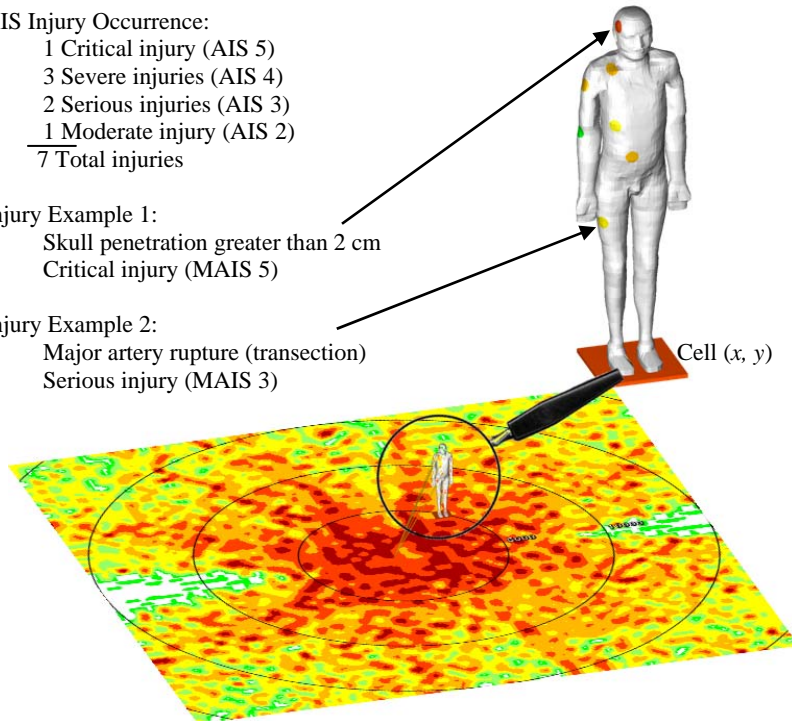


Figure 9. MAIS Contour Plot (highlighting dismounted Warfighter on a single cell)

8. CONCLUSIONS

The survivability provided by different types of body armor systems is influenced by the ballistic protection offered by material armor and its geometric area of coverage. The fit and wear in the field of body armor systems is considered a significant factor in survivability grading from ballistic events. This document defined a survivability assessment process that focuses on the Warfighter and the protection offered by body armor from ballistic penetrating threats. The process was described in five steps: a) measure system dimension and fit; b) construct 3D geometry; c) test and characterize ballistic protection; d) identify and examine unique vulnerabilities; and e) model protection and measure effectiveness. MUVES-S2 with ORCA can be leveraged to model nuances in body armor system configurations in terms of type, size, fit, weight, and add-ons and their effect on Warfighter vulnerability. The sensitivity of observed wear and current wear guidelines are stressed in terms of survivability. While the type of assessment described in our process is not an end-all means for grading body armor systems, it can quantify one of the more critical assessment parameters and thus aid decision makers and personnel protection equipment designers in evaluating benefits versus costs in risk-benefit analysis. A significant lesson learned in performing past survivability analyses was that system vulnerabilities can be effectively addressed in the initial design of future body armor systems.

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APG MD 21005-5055

1 US ARMY EVALUATION CTR
TEAE SV
P A THOMPSON
4120 SUSQUEHANNA AVE
APG MD 21005-3013

12 DIR USARL
RDRL SL
J BEILFUSS
J FEENEY
J FRANZ
M STARKS
P TANENBAUM
RDRL SLB A
D FARENWALD
G MANNIX
RDRL SLB D
R GROTE
RDRL SLB E
M PERRY

NO. OF
COPIES ORGANIZATION

RDRL SLB G
P MERGLER
RDRL SLB S
S SNEAD
RDRL SLB W
L ROACH